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Forecasting Northeastern Pacific tropical cyclone tracks using an analog scheme.

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FORECASTING NORTHEASTERN PACIFIC TROPICAL CYCLONE TRACKS USING AN ANALOG SCHEME

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THESIS

FORECASTING NORTHEASTERN PACIFIC
TROPICAL CYCLONE TRACKS USING AN
ANALOG SCHEME

by

Charles Joel Mauck III

September 1974

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Forecasting Northeastern Pacific
Tropical Cyclone Tracks Using an
Analog Scheme

by

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Submitted in partial fulfillment of the
requirements for the degree of

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September 1974

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I. INTRODUCTION

Tropical cyclone forecasting (development, movement, intensity) is an important and time-consuming task for the Navy meteorologist. Objective guidance is necessary for credible results. Such guidance exists in great abundance for the North Atlantic Ocean (Neumann & Hope, 1973) as well as the western North Pacific Ocean (WESTPAC) areas (Fleet Weather Central/Joint Typhoon Warning Center, 1973). Relatively few objective techniques are available for the eastern tropical North Pacific Ocean (EASTROPAC) area, reputed to be the region of greatest tropical cyclone density (Hansen, 1972). This study treats the forecast problem of tropical cyclone motion in EASTROPAC, encompassing the area from 180 degrees to the North American Coast, and north of the Equator to usually less than 30 degrees North.

Interest in the tropical cyclones of this area was spurred by the introduction of weather satellites in 1964. It became apparent that there existed a far greater frequency of tropical cyclones in EASTROPAC than had previously supposed. (See Table I.) Further, the EASTROPAC cyclone area lies athwart major shipping routes between the Panama Canal and the Far East in addition to coastwise routes between North and South America. In addition to oceanic shipping, this area is a major fishing ground of the west

coast commerical fishing industry. Freeman (1972) tabulated 585 Navy or Navy-contract vessels which made EASTROPAC transits during 1970. The past few years have also seen a great increase in the number of United States registered small, pleasure craft. These are particularly vulnerable to tropical systems and would derive a great benefit from improved forecasts.

When one considers the relatively slow speed of sea-surface transportation, the need for a fairly reliable movement forecast, extended to 48 and 72 hours, becomes obvious. The current modes of forecast used in EASTROPAC are the subjectively derived official forecasts issued by the National Weather Service Forecast Office in Redwood City, California, and the Navy's MOHATT Program (Renard, et al, 1973) run operationally by Fleet Numerical Weather Central, Monterey, California.

Starting in 1969, objective techniques were developed that used an analog concept. Designed for WESTPAC and called TYFOON, one such technique was formulated at the National Weather Records Center (Hodge and McKay, 1970) and subsequently modified by Jarrell and Somervell (1970) at the Navy Weather Research Facility, Norfolk, Virginia, and by Jarrell and Wagoner (1973) at the Fleet Weather Central/Joint Typhoon Warning Center, Guam. Concurrently, a similar technique, called HURRAN, was designed by Hope and Neumann (1970) at the National Hurricane Center in Miami, Florida, for the prediction of the movement of North

Atlantic tropical cyclones. Both techniques are designed to identify past storms containing characteristics similar to the cyclone being forecasted. When the movements of all similar past cyclones are assembled, their average movement is computed and the locations on the average analog track are used as guidance in the issuance of forecasts.

Wagoner (1973) observes that a large portion of the forecaster's subjective prognosis is nothing more than an analog procedure. He simply searches his mind for situations similar to the one presently confronting him. These are then converted into a modified forecast by mentally determining the average outcome of all the situations. The similarity between the mental processes and the analog technique probably explains why the accuracies of the two approaches are comparable.

This study describes the development of an analog technique to forecast the movement of EASTROPAC cyclones to 96 hours. A flow diagram of the step-wise forecast procedure is contained in Figure 1.

II. CLIMATOLOGY AND DATA

A. CLIMATOLOGY

In general, the EASTROPAC cyclones are formed in the eastern section of the area and propagate northward and westward (Figure 2). In the subject area the season extends from mid-May through October with less than one percent of the tropical cyclones forming out of season. An annual average of 14.5 tropical storms form, of which 5.4 become hurricanes, according to a climatology of tropical cyclones in this area, compiled by Hansen (1972). Other pertinent facts from this reference follow. The mean track is toward 292 degrees though this varies with latitude. The mean speed of EASTROPAC cyclones is 10.3 knots with a standard deviation of 3.0 knots. The relative incidence of recurvature is significantly less than the North Atlantic and WESTPAC areas and the most likely time of recurvature is near the end of the season. EASTROPAC cyclones range in size from 1.5 to 5.5 degrees of latitude (mean circular cloud diameter). Their mean area is about half the mean area of WESTPAC tropical cyclones.

B. DATA

Historical data were compiled by the National Climatic Center, Asheville, North Carolina (NCC) and consist of the initial position plus best track 0000 and 1200 GMT positions

for all known tropical cyclones from 1949 through 1973. These data, available on computer punch cards, consist of one position per card, the entire set comprising 2,942 different positions. Because this volume of cards was unwieldy, the data set was compressed to 708 cards. Concurrently with this change of data format all the off-time (non-0000 or -1200 GMT) positions were removed from the history file. In addition, all cyclones which contained less than three positions (after off-time positions were removed) were also eliminated from the file. This has no effect on forecasts as three positions are necessary to make a 24-hour forecast (the minimum forecast interval made in this program).

The next step in the data evaluation involved removal or modification of any positions of tropical cyclones thought to be inaccurate. In the latter category, two cyclones were completely eliminated from the history file. One of these appeared as a March (1951) system located in the middle North Pacific Ocean area and contained a large easterly component of motion. The other was a 1955 hurricane which formed and remained in the North Atlantic area. In the former category, those positions displaying a much larger than normal 12-hour north-south movement (in excess of five degrees latitude) were investigated. One case (a seven-degree movement in the final 12 hours of the storm) was deemed to include a five-degree error and adjusted

accordingly. The net result was a history file covering 25 years and consisting of 257 tropical cyclones with 2666 positions.

Because of the obvious difference in data volume before and after the advent of meteorological satellites (131 storms with 1,043 positions for the 16 years prior to 1965 compared with 126 tropical cyclones and 1,623 positions for the nine years 1965 through 1973), the issues arose as to whether there existed other significant differences in the data. For example, there might be a lack of character in the tracks of early cyclones as compared to the post-satellite era, due to a relative paucity of information. If this were indeed true and statistically significant, then the forecast scheme could be adversely affected; that is, early tracks might have to be disregarded as possible analogs to future tropical cyclones.

To resolve the issue, a smoothness check was run on the data. The check consisted of calculating the distance from the second point of each set of three consecutive points (at 12-hour intervals) to the midpoint between the first and third points. (See Figure 3.) In addition to giving an indication of the eccentricity (deviation from the linear) of the tracks, this procedure gave a measure of curvature. The magnitudes of the vectors labeled R (across track deviation), S (along track deviation), and E (total deviation, R + S) summed and averaged by year and

by period for the time frames in question. For the period from 1949 through 1964, for 781 cases the average magnitude of E (= $\bar{E}$) was 20.8 nmi (variance = 362.4 nmi^2). This was composed of a mean across-track displacement,[1] $\bar{R}$, of -1.9 nmi (variance = 412.5 nmi^2) and a mean along track displacement,[2] $\bar{S}$, of -0.3 nmi (variance = 377.7 nmi^2). For the period 1965 through 1973, for 1,371 cases, $\bar{E}$ was 20.0 nmi (variance = 251.5 nmi^2), $\bar{R}$ was -1.6 nmi (variance = 255.1 nmi^2) and $\bar{S}$ was 0.6 nmi (variance = 392.5 nmi^2).

The results obviously negated the original hypothesis that the earlier tracks were smoother. In fact, it seemed to imply that the earlier tracks were significantly more eccentric than the post-satellite period tracks. The data set was again checked and those individual points contributing the most to the variance were checked. The majority of these fell into a category involving recurvature which would result in a large across-track displacement. To further investigate the eccentricity of the two periods, the across-track, along-track and mean total displacements were again computed, then normalized by dividing the displacements by one half the total 24-hour movement magnitude ($|\vec{V}|$). (See Figure 3.) These results were again totaled and averaged by year and period. (The results are contained in Tables II and III.) Once again there seemed to be a

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[1]Negative numbers indicate anticyclonic curvature of the track.

[2]Negative numbers indicate deceleration along the track.

significant difference in the variance of eccentricity between the two periods. Again, the early period appears to be significantly more eccentric than the post-satellite years (early period variance = 0.116 vs later period variance = 0.048). As before, the points making the greatest contribution were individually inspected and there were very few points that made a large contribution to the variance of both the original and the normalized set of data. Those points making the largest contributions primarily to the normalized set were cases in which there was very little 24-hour movement but a relatively large displacement of the middle point (B) from AC (in Figure 3) such as in a cyclone that had in reality looped but was held in the best-track data as relatively stationary.

Because no real conclusions were drawn as to the true significance of the possibly greater eccentricity of the earlier tracks or the effect on the forecasts, the option to drop the data from 1949 through 1964 was held open throughout the development of the forecast technique. The problem was only resolved in the final test and evaluation. (See Chapter IV.)

III. TEST CASES

Some form of test cases or test positions is required at all phases during the forecast technique development cycle (Figure 4). Ideally it is preferred to have one set of cases with which to perform any routine testing during development and an entirely independent set of cases for testing the final forecast technique. This independence would improve the probability of detecting forecast instability during testing. Hence, there would be a high probability that the forecast technique would perform in the same manner in an operational environment as in the controlled test environment.

To accomplish this statistical independence entails the use of a large sample of test cases (a few hundred), none of which could use as analogs those cyclones which contain any of the test cases. However, the limited size of the present data set for EASTROPAC makes this unrealistic (257 named cyclones with 2,666 positions). To circumvent this problem, two different sets of test data were used. For the final verification of the technique, use was made of an existing set of 1973 operational positions, from which official and MOHATT (Renard et al, 1973) forecasts had been made. This set presented an opportunity to compare the verifications of the analog technique with an

operationally used objective technique as well as subjective official forecasts.

However, prior to making these operational-type forecasts a set of easily accessed, changeable and readily verified test positions were needed. Because several modifications would be attempted, the identical positions would need to be recalled and the results from each of the modifications compared with the previous attempts.

A test-position generator was incorporated as a removable component in the forecast program. The key to the selection of the test position is a random number which is generated internally. The test candidates are contained within the history file. After a candidate for a test position is screened to insure at least the required amount of history and verifying positions (for example, in a 72-hour forecast at least six successive positions are required for verification), the random number subroutine generates a number between zero and 100. This is compared with a specified number (adjustable due to computer turn-around time limitations) corresponding to the percentage of cases (out of possible 2,152) desired, and if the generated number is less than this number, then, this position is "selected" as a test case.

After a test case had been selected, the 12- and 24-hour history positions (if required) were retrieved from the file. Next, the initial and 12-hour history positions

were contaminated to simulate an operational error using a subroutine in the program which computed a 24-hour error by a "Monte Carlo" technique (Hillier and Leibermann, 1967) applied to the cumulative frequency distribution (Figure 5) of 24-hour typhoon forecast errors in WESTPAC (FWC/JTWC, 1971). Depending upon the simulated time interval since the last fix, a predetermined portion of the simulated 24-hour error was added (as a two-component vector) to the initial position and one-half that initial position error was added to the 12-hour history position.

In WESTPAC the distribution of warning-position errors is very well described by using that percentage of the 24-hour forecast error which is dependent on the fractional part of the 24-hour period elapsed since the last fix. (See Figure 5.) WESTPAC warnings are based on reconnaissance fixes which are almost always within the past six hours, with the maximum frequency at scheduled fix times (i.e., two hours before warning time), and an average estimated to be about an hour earlier than scheduled fix time.

Four classes of positions, dependent on the time interval since the last reconnaissance or a good satellite fix, was considered. (A good satellite fix is one in which the words good or excellent are used in the subsequent warning message to describe the position accuracy.)

Since, as stated above, the WESTPAC fix time is, on the average,about three hours prior to warning time (i.e.,

time from which forecast interval is counted) the 24-hour forecast is in reality a 27-hour forecast.

Error magnitudes were given by entering Figure 5 (for 24 hours) with a random number (between zero and 100). After the proper portion of the selected magnitude had been taken, depending on time since the last fix, a second random number distributed the error into equally likely positive zonal and meridional components. A third random number determined the quadrants,relative to the cyclone center,containing the error vector.

IV. FORECAST TECHNIQUE DEVELOPMENT

A. INTRODUCTION

The assumption is made that a pure analog forecast scheme will not perform satisfactorily. A pure analog scheme is defined as one where history is searched for a situation analogous to an existing situation. Such an analog is found and the subsequent behavior of this analog is used directly as a forecast of the future of the existing situation. Pure analog schemes, for tropical cyclone forecasting, have failed for two reasons. First, good analog pairs (those whose future are closely parallel) are not common enough to presuppose a single good analog could be found for most forecast situations. Secondly, there are no known methods for reliably discriminating poor analogs from ordinary analogs or ordinary analogs from good analogs. Hence, there exists no method to select a superior analog if one exists.

One way around the dilemma is to use some sort of screening to separate the analogs into groups, ranging from the best to the worst. In a statistical sense this is possible; that is, one can separate the analogs into groups which are better (or worse) than average performers. Generally, analog schemes have tried to separate analogs into two groups: "good enough" and "not good enough". The "not good

enough" group are then ignored and the "good enough" group forms the basis of the forecast. Usually these are composited into a single analog forecast using an ordinary or weighted average after each has been adjusted for any systematic (and predictable) differences between it and the cyclone being forecast.

The variations between analog schemes fall into three areas: (a) how is "good enough" determined or what sort of screening or filtering should be used to eliminate unacceptable analogs, (b) how to correct or adjust for discernable differences between the existing cyclone and an analog cyclone, and (c) how to composite the group of adjusted "good enough" analog tracks.

B. DETERMINING ACCEPTABLE ANALOG

How good is "good enough?" If each analog track is viewed as an independent, unbiased estimate of the track to be forecast, then the central limit theorem suggests that as one makes more estimates, the average of these estimates should converge toward the true value being estimated. While independence is by no means assured (in fact dependence is the basis of analog forecasting), the widely accepted preference of a composited over a single analog track is in itself endorsement of the concept of improvement in forecasts as the number of analogs in the composite increases. Since the period of retrievable history is

severely limited (especially in EASTROPAC), there is an upper limit on the possible number of analogs. Within this limit, the number of analogs actually used depends upon the definition of "good enough." As we relax our criteria for "good enough," we increase the number of analogs, but we draw more from a population of not-so-good analogs. Obviously, we would like to define the "good enough" cut-off point as that point where the improvement brought about by increasing the number of analogs exactly balances the detrimental effect of including worse analogs and beyond which the net effect is to decrease the accuracy of forecasting the cyclone track.

A measure of goodness. When two tropical cyclone tracks are compared, it is desirable to have some measure of similarity between them. There are certain differences between any two cyclones at the point of origin (of the forecast) that may help explain future differences. If so, these explanable future differences should be removed before a yardstick of similarity is applied. The method adopted here to accomplish this involved running least-squares regression to predict that portion of the track difference between two tropical cyclones after 48 hours which was not present at the common starting points (starting points are randomly chosen along the two tracks). A list of predictors are found in Appendix A. The unexplained variance (sum of meridional and zonal components) is then a measure of the dissimilarity between each pair of cyclone tracks.

As a point of departure, a set of five symmetric screens was established, patterned after Jarrell and Somervell (1970). The screens are:

1. Latitude difference between two origin points (TY)

2. Longitude difference between two origin points (TX)

3. Relative meridional movement between two cyclones over the prior 12 hours (BY)

4. Relative zonal movement between two cyclones over the prior 12 hours (BX)

5. Difference in Julian dates of origin points (DD)

Several hundred different combinations of symmetric cut-off values for these screens were subjected to regression analysis. Recorded for each such test was the unexplained variance and number of cyclone pairs passing through all five screens.

Only the 1965-73 history file was used in this effort. This limited the history to 126 tropical cyclones and 1,623 positions. Once the first of the pair of points was selected, all the other 1,622 points (except those of the cyclone which contained the first point) were eligible to play the role of the second of the pair of points. The maximum possible number of pairs was in excess of one million. By use of a random selection, the number of pairs was restricted to a few percent of the total possible (usually 10,000 to 50,000).

From these hundreds of runs there were constructed rough curves of the rate of change of unexplained variance

with a unit change in a particular screen setting and also the change in the rate of acceptance (number of pairs passing a screen divided by the number of pairs subjected to screening) with a unit change in screen setting. Both measures represent approximations to partial derivatives since all other screens were held constant at various values over their possible range. By a process of successive approximations those optimum (minimum total unexplained variance) screen settings were determined which permitted a given percentage of the matched pairs to pass. Optimum screen settings were determined for acceptance rates of five to 50 percent in increments of five percent. These screen settings are given in Table IV. A sample of 371 48-hour test forecasts were made at each acceptance level up to 30 percent. Mean error, root mean square (RMS) error, number of cases, and failure rate are also given in Table IV for each of these acceptance settings. (A failure here was defined as a case where two or less analog cyclones were usable. This was considered an invalid forecast. This cut-off was later changed from two to ten.) Notice that the minimum average and RMS errors occur near an acceptance rate setting of 15 percent. This suggests that the set of screen settings corresponding to 15 percent is near the point of optimum trade-off between the advantage of more analogs and the disadvantage or accepting more "not-so-good" analogs.

When considering adoption of 15 percent settings another facet of the problem appeared. The failure rate of over nine percent is high. For a forecaster to get a "sorry about that" message nine percent of the time leaves something to be desired. It was arbitrarily decided that a failure rate greater than five percent was unacceptable if it were possible to bring the failure rate to below that level without appreciable loss of forecast accuracy.

With this thought in mind, the screen settings selected were those corresponding to the 30 percent (acceptance) settings. The 30 percent settings possessed a failure rate of around two percent. While this would appear to be setting standards too low, these forecasts were based on best-track data with no initial position error and with only two analog cyclones required for acceptance. With the addition of an initial-position error and a change to at least ten analog cyclones for acceptance, the failure rate at 48 hours for even the 30 percent settings significantly increased.

C. ADJUSTING ANALOG FOR BEST COMPARISON TO EXISTING CYCLONE

Once the screens are set, the question arises as to how one adjusts the analog track to remove the discernable difference between the analog and current tropical cyclones.

The obvious first difference is that of position. (Note that this is the basis of the first two screens.)

To account for this difference all the points (past, present, and future) on the analog track are "translated" or adjusted (Figure 6) by the amount of the vector from the analog origin position to the origin of the current cyclone (TX and TY, as defined earlier). After this adjustment has been made, the next obvious difference in the tracks was the past movement. (Recall that past 12-hour motion differences are screen parameters.) In addition to the 12-hour past movement differences (12-hour bias), the 24-hour past movement differences were also calculated.

There were several ways that an adjustment might have been made to the analog track. TYFOON-72 (Jarrell and Wagoner, 1973) vectorily added in the equivalent of the 12-hour bias at each 12-hour forecast interval (i.e., the 48-hour bias is four times the 12-hour bias; see Figure 7) while in the Atlantic HURRAN (Hope and Neumann, 1970) applied the 12-hour bias at a decreasing rate with forecast interval (ranging from the entire amount of bias for a 12-hour forecast to a maximum at 36 hours and beyond).

In EASTROPAC it was decided to use regression equations to determine the best bias adjustment. In order to accomplish this task, the program for the aforementioned regression analysis and the forecast program were combined and a new set of regression equations for the bias were written. Equations were written using a random sample of around 500 cases. A different set of equations for the

latitude and longitude components of bias was written depending upon the time since the last fix (simulated to be 3, 9, 15, or 21 hours), the amount of history given (zero, 12, or 24 hours) and each forecast interval (24, 48, 72, or 96 hours). In total, 96 different equations were developed. Fifty variables were available for entry into the regression equation. However, only the most significant ones were used; those which, upon entering, explained less than an additional 1 percent of the total variances were not used.

D. COMPOSITING ANALOGS IN THE FORECAST

When the history file is exhausted and all analogs have been screened and those considered "good enough" have been adjusted for position and movement, the problem of finding some method of compositing the storms into a single forecast remains. Once again there are different methods by which this might be accomplished. One might composite with a simple average or by some weight attached to each analog forecast.

It was decided to use this latter method in EASTROPAC in view of the liberal screens used in order to insure making a reasonable amount of forecasts. By down-weighting those factors far removed from the mid-point of the acceptance region it was felt the average error might be brought more in line with the 15 percent case. To accomplish the compositing, two types of weighting factors were

multiplied to form a single weight. The first factor reflected the statistical fact that analogs with a screen parameter far removed from that of the current cyclone is more likely to produce a poor forecast than one closer. The second factor reflected the supposed lesser accuracy of analogs which have no past history (or only 12-hour history).

Several parameters were tried in an effort to establish the first weight factor and all involved some measure of the probability of a good 48-hour forecast (error less than 180 nmi) and the probability of a bad forecast (error greater than 240 nmi). On a test sample of 363 cases the best weighting factor was

$$W = \prod_{j=1}^{5} \left(P_{i,j} \frac{P_{Gi,j}}{P_{Bi,j}}\right) , \qquad (1)$$

where $P_{Gi,j} (P_{Bi,j})$ is the probability of a good (bad) forecast given that the ijth class has occurred. The j reflects the five different screens and i reflects that each screen interval is divided into five regions. This weighting factor had little influence on the total RMS error, except for those cases with a small number of analog storms (less than 20). The apparent influence on these cases was to make their error distribution fall in line with that of cases using large number of analogs.

The second weighting factor reflected the fact that better forecasts resulted from a longer history (a manifestation of a persistence contribution). Weighting factors (meridional and zonal components) consisted of the reciprocal of the variance of error ($1/s^2$). There was no statistical difference in the variance of the latitude component of error (perhaps due to small acceptable range of meridional motion) but zonal variances were markedly different for 12-hour history compared to no history but somewhat less different for 24-hour history versus 12-hour history. Any difference diminished as initial-position error increased (since indicated past motion became a less reliable index of future motion). Thus, these weighting factors were really important only when a good history was available. Additionally, history was most important in a 24-hour forecast and least important at 96 hours. Note that if no history was available for the current storm, history on an analog storm was immaterial therefore the weighting factor was only used when the current cyclone history equaled or exceeded the analog history.

E. MODIFICATIONS TO ANALOG PROGRAM FROM DEVELOPMENT TEST RUNS

At this point the technique was run on a set of 551 simulated test cases. A record was kept (see Table V) of the average error, RMS error and number of forecasts verified at each forecast interval, using varying amounts

of history and simulated initial position errors. Then proposed modifications (largely simplifications) were tested (one at a time) and the results compared with the above. In the end four significant modifications were made to the program. (A trial modification was retained if either there was no significant increase in the errors or no significant decrease in the number of forecasts verified.)

The first modification was that each individual analog position was considered independently. Prior to this all the forecasts from the positions on a single analog cyclone were weighted and averaged. Then all these average positions from the analog cyclones were composited for the final forecast positions. However, the requirement that a valid forecast must have a contribution from at least ten difference cyclones was retained.

The second modification involved testing the significance of the regression equations. All the regression equations for the latitude bias correction were found to give no appreciable decrease in the error and were eliminated. This is probably because of the relatively small screen size on the 12-hour latitude bias and was suspected because of small amount of variance explained. Also eliminated were the longitude bias correction equations when no history was present. In any case forecasts in the absence of history are entirely a climatological average.

The third modification made to the forecast technique concerned the weighting factors. The program was run with no weights, just weights on one component (latitude or longitude), and combinations with only one of the two weighting factors in the multiple. In the final analysis the latitude weighting factor was eliminated. Here again it was felt that the relatively small latitudinal screen size made any weight here insignificant.

To test a possible fourth modification, the forecast technique was run again on the set of internally generated test positions in order to examine the practicality of dropping that portion of the history file prior to 1965. In this trial the cyclones occurring prior to 1965 were excluded as possible analog candidates (though they were utilized as test positions). The results indicated no appreciable change in accuracy and a sharp decrease in the percentage of forecasts made (due to decreased analog population). In view of these results, it was decided to keep the history file intact.

The final modification was to correct a problem which sometimes results from permitting those analog points with no history (first point on an analog track) to be considered when points with history are available. In the absence of analog history, past relative motion cannot be computed; therefore, two screens are inactive, and a disproportionately large number of no-history points may enter the "good-enough" fold. This is particularly troublesome

when the past motion of the current cyclone is climatologically unusual and proportionally few analogs are permitted through the relative motion screens. In these cases an abnormally high percentage of analogs making up the composite are "no-history" cases. Hence, the forecast is climatology dominated, in a situation where recent motion has not followed climatology. To cure this problem, a check is made to see if the number of no-history cases exceeds that upper limit of the proportion of the total expected by chance alone only five percent of the time. In these cases, all "no history" analogs are excluded from the forecast. This modification increased the number of occurrences of failure to make a valid forecast, but it did significantly improve a group of poor forecasts.

F. ANALOG FORECAST FORMAT

The forecasts from this technique are output as a center position and extreme points on the minor and major axes of a 50 percent probability ellipse. Both TYFOON 72 (Jarrell and Wagoner, 1973) and HURRAN (Hope and Neumann, 1970) use probability ellipses.

The probability ellipses of the distribution of a bivariate normal (Gaussian) population are given by the following equation:

$$\frac{1}{1-r_{xy}^2}\left(\frac{x-\bar{x}}{s_x}\right)^2 - 2r_{xy}\left(\frac{x-\bar{x}}{s_x}\right)\left(\frac{y-\bar{y}}{s_y}\right)+\left(\frac{y-\bar{y}}{s_y}\right)^2 = k^2 \qquad (2)$$

where x and y are the two random variables and can represent orthogonal components of a forecast error vector; $\bar{x}$ and $\bar{y}$ are the sample means; S_x and S_y are the sample standard deviation; and, r_{xy} is the sample correlation coefficient. The constant, k^2, has a chi square (χ^2) distribution with two degrees of freedom and the values of χ^2 are tabulated for any desired level of probability. The geometric center of the ellipse is the point $\bar{x}$, $\bar{y}$, (United States Naval Weather Research Facility, 1963).

V. RESULTS AND CONCLUSIONS

A. RESULTS

The final forecast technique, henceforth referred to as NPEHAT (Northeast Pacific Hurricane Analog Tracker), was subject to two types of testing. First, a group of simulated forecasts were made for comparative purposes. The verification results of these tests are given in Table V. NEPHAT forecasts were made for 24, 48, 72, and 96 hours under four classes of simulated initial position errors (see Chapter III). The following results are apparent. First, the average error is heavily dependent upon the validity of the initial position. Second, the forecast technique appeared to give highly satisfactoty forecasts, especially when the initial position is based on a relatively recent fix.

In order to further investigate the validity of the above results, the 1973 best track data were removed from the history file and the forecast technique was run on 1973 operational positions for which official and MOHATT forecasts existed. The homogeneous test set consisted of warning positions for nine named tropical cyclones and two tropical depressions. All operational (warning) positions were ones for which at least a 24-hour forecast could be verified.

The results, on a cyclone by cyclone basis and stratified according to synoptic time and forecast interval, are contained in Table VI. Two particular cases are worthy of discussion at this point.

Hurricane Doreen was a relatively long-running cyclone (16 days) and possessed a zonally oriented track. (Figure 8). The cyclone was fairly typical of the climatology in EASTROPAC with the possible exception of a generally southwestward motion during the period 26 through 29 July. The average forecast errors are also contained in Table IV and include forecasts from all four synoptic times. It should be noted that at 24, 48, and 72 hours, the average forecast errors for Doreen are less than the average predicted from the simulated cases (Table V) with the least initial position error. Most of the reconnaissance fixes taken on Hurricane Doreen were near 1800 GMT, thus forecasts made from near this time tended to exhibit increased accuracy.

The other significant case considered Tropical Storm Jennifer. This was a relatively short-lived cyclone (four days) occurring near the end of September. The recurvature track (Figure 9) is considered atypical of EASTROPAC cyclones (though it did occur during the period of peak recurvature frequency). Jennifer formed near 13.2N, 113.6W and moved in a northeasterly manner during the entire period, accelerating during the last two days. There were neither

aircraft fixes nor good satellite fixes during the entire lifespan of this storm. Two items stand out as significant with respect to NEPHAT's performance on this cyclone- First, due to the size of the history file relatively few analogs were located, thus no NEPHAT forecasts were possible at many synoptic times. Secondly, the relatively large average forecast errors for this storm were probably attributable to both the atypical movement and the absence of fixes. This latter conclusion is best demonstrated by considering the 1200 GMT forecasts on 23 September. The warning position was 13.3N, 116.5W with a 12-hour past movement of 0.1 degree north and 2.9 degrees west. This is compared with the best-track position at 1200 GMT on 23 September of 13.3N, 113.4W with a 12-hour movement of 0.1 degree north and 0.2 degrees east. This pseudo westward movement was readily accepted by NEPHAT and 24, 48, and 72 hour forecasts based on 107, 92, and 81 analog positions, respectively, were made. The errors for this set of forecasts were: 472 nmi at 24 hours, 877 nmi at 48 hours, and 1,156 nmi at 72 hours, thus reinforcing the importance and necessity of a fairly reliable fix for accurate NEPHAT results.

Table VII details the average forecast error by cyclone stage and forecast interval. These results suggest that NPEHAT performs best on the more intense tropical cyclones although the techique was developed without regard to cyclone stage and tacitly intended for all stages.

A comparison of forecast technique errors before and after recurvature (Table VII) shows that NEPHAT errors were significantly less (nearly half) for tracks prior to recurvature. This results from a greatly increased zonal error component in the after-recurvature cases. The increase is primarily due to the small historical frequency of eastward moving cyclones in EASTROPAC and reflects the domination of that small stratification by the errors associated with Tropical Storm Jennifer.

The next step in the verification phase of the technique was comparison of NEPHAT forecast errors with the only other technique presently used in the EASTROPAC area, MOHATT (Renard et al, 1973) and the official forecast (subjective). The NEPHAT errors were compared with the MOHATT forecasts (based both on 850-mb and 700-mb steering). These results are contained in Tables VIII and IX, respectively. It appears that the NEPHAT forecast errors are significantly less than either of the MOHATT modes at all forecast intervals and all synoptic times. However, the MOHATT (700 mb) technique did approach NEPHAT at 24 and 72 hours for the synoptic verification time of 0000 GMT. The greatest difference in average errors, NEPHAT vs MOHATT, occurred at the 1800 GMT synoptic verification time. Since this is near the average fix time in EASTROPAC this would give the NEPHAT technique its best results, while the nature of the MOHATT scheme makes this verification time predictably its poorest.

Upon comparison with the official forecast errors for these same 1973 cases one finds that the errors from the NEPHAT technique are less (Table X). There is one exception, namely for 24-hour forecast verifying at 0600 GMT, at which time the official forecast out-performed the NEPHAT technique. At all other synoptic times and forecast intervals the NEPHAT technique errors were slightly less than the official errors. Unlike the MOHATT technique, the greatest error difference occurred for a synoptic time of 1200 GMT.

B. CONCLUSIONS

Based on these results it was concluded that the NEPHAT technique has the potential for a valuable aid in forecasting the movement of EASTROPAC tropical cyclones.

Since most reconnaissance fixes are made at about 1800 GMT, we assumed that 1800 GMT corresponds to that "time since fix" nearest to three hours and subsequent synoptic times 0000, 0600 and 1200 GMT correspond to "time since last fix" nearest to 9, 15 and 21 hours, respectively in Table V. With this assumption, the simulated results of Table V can be directly related to the operational test results of Table VIII, IX, or X. Such a comparison is made in Table XI. The similarity in average errors of forecasts from simulated test positions and actual operational positions infer that the technique outlined in Chapter III for generating simulated positions and the usage of those

positions in the program development was realistic. Such similarity also tends to confirm that the usage of the "Monte Carlo" type simulation realistically modeled the operational uncertainty in positioning.

APPENDIX A

The predictors used in the regression analysis described in Chapter IV were constructed by multiplying each of the items contained in List 1 by each of those items appearing in List 2.

<u>LIST 1</u>.

1. Latitude difference at points of origin (TY)
2. Longitude difference at points of origin (TX)
3. 12-hr meridional relative motion (BY)
4. 12-hr zonal relative motion (BX)
5. Date difference at points of origin (DD)

<u>LIST 2</u>.

1. 1.0
2. Latitude of current cyclone (YCO)
3. Longitude of current cyclone (XCO)
4. Julian date of current cyclone (D)
5. YCO^2
6. XCO^2
7. D^2

TABLE I

Number of eastern tropical North Pacific Ocean cyclones and the average number of 0000 or 1200 GMT positions from 1949 through 1973

YEAR	NUMBER OF CYCLONES	AVERAGE NUMBER OF POSITIONS (0000 OR 1200 GMT)
1949	6	7.0
1950	7	10.5
1951	9	7.5
1952	7	6.7
1953	4	7.0
1954	12	10.3
1955	5	7.0
1956	9	6.2
1957	10	12.5
1958	12	7.6
1959	13	7.8
1960	7	9.7
1961	9	5.2
1962	9	7.1
1963	7	5.6
1964	5	6.4
1965	10	12.1
1966	13	12.1
1967	16	13.7
1968	18	13.1
1969	12	9.1
1970	17	11.8
1971	17	13.9
1972	12	16.0
1973	11	13.9
1949-64	8.1	8.0
1965-73	14.0	13.0

TABLE II

Mean and variance of EASTROPAC tropical cyclone track eccentricity by year. E defined as total eccentricity while R represents across track and S is along the track (see Figure 3).

YEAR	CASES	MEAN(E) (NMI)	VAR.(E) (NMI^2)	MEAN(R) (NMI)	VAR(R) (NMI^2)	MEAN(S) (NMI)	VAR.(S) (NMI^2)
1949	30	19.6	418.1	-0.4	455.9	0.5	344.5
1950	60	14.4	99.9	-0.3	132.8	-1.2	171.5
1951	50	23.1	637.8	-5.6	564.8	-0.4	571.8
1952	33	14.1	69.3	-2.1	93.1	0.7	169.3
1953	20	14.5	109.7	-0.4	125.5	4.8	181.2
1954	100	23.7	222.0	0.7	373.8	-0.1	405.0
1955	25	20.1	114.4	-2.3	265.7	0.5	247.6
1956	38	19.1	194.3	2.5	335.9	-2.1	212.8
1957	105	27.6	522.9	-3.3	620.8	0.9	651.8
1958	68	17.9	816.2	-4.3	717.7	-2.9	392.5
1959	76	22.3	258.3	0.1	272.1	0.1	483.6
1960	54	19.4	185.0	-1.6	264.9	-0.7	295.2
1961	29	18.9	306.2	-8.3	321.0	0.9	273.9
1962	46	14.9	206.5	-5.4	246.6	0.9	152.2
1963	25	32.6	746.1	-0.6	1162.9	-2.5	636.5
1964	22	16.7	66.1	1.5	267.2	-0.6	75.2
1965	101	14.8	88.2	-1.9	149.9	0.6	153.1
1966	131	21.3	209.3	-2.2	245.7	-0.3	413.0
1967	187	22.4	374.2	-2.2	375.9	-0.3	494.7
1968	200	19.2	207.4	-0.6	263.2	-0.2	313.9
1969	85	19.2	236.8	-0.6	239.1	0.1	365.4
1970	166	15.9	149.5	-1.6	199.4	1.7	198.0
1971	202	21.2	213.8	-2.3	269.5	-0.1	386.9
1972	168	22.3	323.7	-2.8	218.9	-1.1	595.2
1973	131	21.1	352.6	0.0	258.6	0.3	537.8
49-64	781	20.8	362.4	-1.9	412.5	-0.3	377.7
65-73	1371	20.0	251.5	-1.7	255.1	0.1	392.5

TABLE III

Normalized mean and variance of EASTROPAC tropical cyclone track eccentricity by year. E is defined as the total eccentricity $(R^2+S^2)^{1/2}$. R represents the across-track difference and S is along the track. Due to the normalization process these parameters are dimensionless.

YEAR	CASES	MEAN(E)	VAR.(E)	MEAN(R)	VAR.(R)	MEAN(S)	VAR.(S)
1949	30	.250	.037	-.019	.051	.006	.048
1950	60	.187	.021	.001	.024	-.014	.032
1951	50	.337	1.390	-.151	.996	-.086	.477
1952	33	.171	.012	-.031	.018	.013	.022
1953	20	.190	.013	.003	.020	.039	.028
1954	100	.238	.020	.010	.037	-.004	.041
1955	25	.295	.031	-.049	.065	.006	.051
1956	38	.152	.006	.009	.015	-.023	.013
1957	105	.238	.041	-.020	.055	.015	.042
1958	68	.158	.020	-.023	.022	-.009	.023
1959	76	.230	.024	-.004	.037	.000	.040
1960	54	.189	.015	-.009	.029	-.004	.021
1961	29	.224	.116	-.109	.119	.011	.034
1962	46	.173	.013	-.049	.017	.021	.023
1963	25	.290	.052	-.031	.086	-.018	.049
1964	22	.138	.004	.018	.017	-.011	.005
1965	101	.159	.014	-.018	.022	.007	.017
1966	131	.232	.037	-.022	.046	.000	.045
1967	187	.212	.030	-.024	.036	-.002	.039
1968	200	.176	.037	.002	.040	.001	.028
1969	85	.264	.120	-.016	.066	.016	.123
1970	166	.195	.119	-.010	.037	.042	.118
1971	202	.195	.019	-.025	.026	.002	.030
1972	168	.224	.034	-.016	.022	-.016	.062
1973	131	.207	.044	-.002	.025	.001	.062
49-64	781	.218	.117	-.025	.102	-.005	.062
65-73	1371	.204	.048	-.028	.035	.003	.055

TABLE IV

Optimum screen settings obtained by changing the percentage of positions selected as analog candidates. The test results are included for those percentages between five and thirty.

Acceptance Ratio (%)	Optimum Screen Settings TY °Lat	TX °Lat	BY °Lat	BX °Lat	DD Days	48-Hour Forecast Test Results Av. Err. (nmi)	RMS Err (nmi)	Failures number	(out of 371) percentage
5	0.8	12.0	0.1	0.6	180	170.6	196.4	132	36
10	1.2	12.0	0.5	0.8	180	160.7	184.4	42	11
15	1.5	12.0	9.5	1.6	180	158.7	180.8	34	9
20	1.5	12.0	0.6	1.6	180	163.4	188.6	29	8
25	1.5	21.0	0.6	1.6	180	163.6	187.8	23	6
30	1.5	72.0	0.6	1.8	180	172.6	198.6	8	2
35	1.8	72.0	0.7	1.8	180	-	-	-	-
40	1.8	72.0	0.8	1.8	180	-	-	-	-
45	1.8	72.0	0.9	2.0	180	-	-	-	-
50	1.8	72.0	1.1	2.4	180	-	-	-	-

TABLE V

The results of the NEPHAT forecast technique on the randomly selected test cases incorporating a simulated initial position error.

TIME SINCE LAST FIX	FORECAST INTERVAL (HOURS)	FORECASTS MADE NO.	(%) of POSS.	AVERAGE ERROR (NMI)	RMS ERROR (NMI)
3 hours	24	521	96	91.5	108.0
	48	405	96	171.6	202.3
	72	309	94	247.0	289.0
	96	219	93	316.5	365.3
9 hours	24	516	95	106.8	124.8
	48	397	94	180.9	213.1
	72	307	93	254.6	297.4
	96	217	92	324.8	376.1
15 hours	24	511	94	128.4	149.6
	48	396	93	202.0	239.2
	72	298	91	265.0	312.3
	96	212	90	333.0	387.0
21 hours	24	495	93	148.8	174.1
	48	378	89	222.5	264.0
	72	286	87	274.5	324.0
	96	204	86	345.7	403.0

TABLE VI

1973 NEPHAT forecast results by storm and forecast interval. Operational position data were used to initiate forecasts. The number of forecasts is contained in parentheses.

CYCLONE	AVERAGE ERROR (NMI) 24-HOUR	48-HOUR	72-HOUR
AVA	124.9 (25)	231.2 (23)	323.1 (21)
CLAUDIA	204.2 (7)	307.1 (3)	
DOREEN	87.4 (46)	165.5 (42)	237.0 (38)
TD-5	42.5 (5)		
EMILY	85.7 (23)	134.4 (19)	145.7 (15)
FLORENCE	78.0 (15)	98.4 (11)	133.2 (7)
GLENDA	107.6 (15)	147.1 (11)	151.8 (8)
TD-10	145.5 (6)		
IRAH	111.4 (12)	230.5 (8)	327.6 (4)
JENNIFER	346.6 (6)	672.6 (4)	1156.3 (1)
KATHERINE	100.1 (30)	235.0 (25)	394.3 (23)
LILLIAN	97.1 (13)	169.6 (10)	197.0 (6)
TOTAL	110.2 (199)	195.8 (156)	267.0 (123)

TABLE VII

NEPHAT 1973 forecast results by stage and forecast interval and relative to recurvature. Operational position data were used to initiate forecasts. The number of forecasts is contained in parentheses.

STAGE	AVERAGE ERROR (NMI)		
	24-HOUR	48-HOUR	72-HOUR
TROPICAL DEPRESSION	143.2 (34)	246.3 (22)	252.8 (14)
TROPICAL STORM	129.0 (79)	211.6 (61)	285.4 (57)
HURRICANE	79.9 (86)	167.4 (73)	250.6 (52)
BEFORE RECURVATURE	102.1 (189)	181.2 (148)	258.5 (119)
AFTER RECURVATURE	263.1 (10)	466.6 (8)	518.2 (4)

TABLE VIII

Comparison of average forecast errors between NEPHAT and MOHATT (850-mb steering), 1973, eastern North Pacific Ocean.

	AVERAGE ERRORS (NMI)								
	24-HOUR			48-HOUR			72-HOURS		
GMT	CASES	MH850	NEPHAT	CASES	MH850	NEPHAT	CASES	MH850	NEPHAT
0000	46	119.8	106.3	32	213.3	182.3	25	311.6	278.4
0600	47	144.6	111.5	35	269.5	196.5	24	355.9	317.3
1200	52	151.3	126.6	41	282.0	213.0	30	397.9	249.4
1800	51	154.3	99.1	32	304.7	165.3	24	485.2	253.7

TABLE IX

Comparison of average forecast errors between NEPHAT and MOHATT (700-mb steering), 1973, eastern North Pacific Ocean.

	AVERAGE ERRORS (NMI)								
	24-HOUR			48-HOUR			72-HOUR		
GMT	CASES	MH700	NEPHAT	CASES	MH700	NEPHAT	CASES	MH700	NEPHAT
0000	46	108.7	105.7	31	231.7	176.7	20	308.6	297.0
0600	46	144.3	110.6	36	299.2	203.9	24	355.6	318.5
1200	52	158.6	126.6	38	264.3	202.4	27	409.8	275.9
1800	50	150.5	98.4	30	252.8	168.3	20	363.1	275.3

TABLE X

Comparison of average forecast errors between NEPHAT and the OFFICIAL (National Weather Service) forecasts, 1973, eastern North Pacific Ocean.

	AVERAGE ERROR (NMI)								
	24-HOUR			48-HOUR			72-HOUR		
GMT	CASES	NEPHAT	OFF'L	CASES	NEPHAT	OFF'L	CASES	NEPHAT	OFF'L
0000	48	101.0	104.0	36	171.6	202.7	29	253.9	277.7
0600	47	111.5	108.0	33	191.1	202.5	27	278.5	298.8
1200	53	127.9	138.9	32	198.3	234.3	26	271.2	337.1
1800	51	99.1	106.0	33	176.5	218.9	23	249.1	270.7

TABLE XI

A comparison of mean NEPHAT forecast errors (in nmi) between the test cases with the simulated error and the 1973 operational (warning) fixes. The number of cases in each sample is given in parenthesis.

	Forecast Interval (hrs)		
	24	48	72
Simulated by 3-hours since the last fix	91.5(521)	171.6(405)	247.0(309)
Operational from 1800 GMT	99.1(51)	176.5(33)	249.1(23)
Simulated by 9-hours since the last fix	101.8(516)	180.9(397)	254.6(307)
Operational from 0000 GMT	101.1(48)	171.6(36)	253.9(29)
Simulated by 15-hours since the last fix	128.4(511)	202.0(396)	265.6(298)
Operational from 0600 GMT	111.5(47)	191.1(33)	278.5(27)
Simulated by 21-hours since the last fix	148.8(495)	222.5(378)	274.5(286)
Operational from 1200 GMT	127.9(53)	198.2(32)	271.2(26)

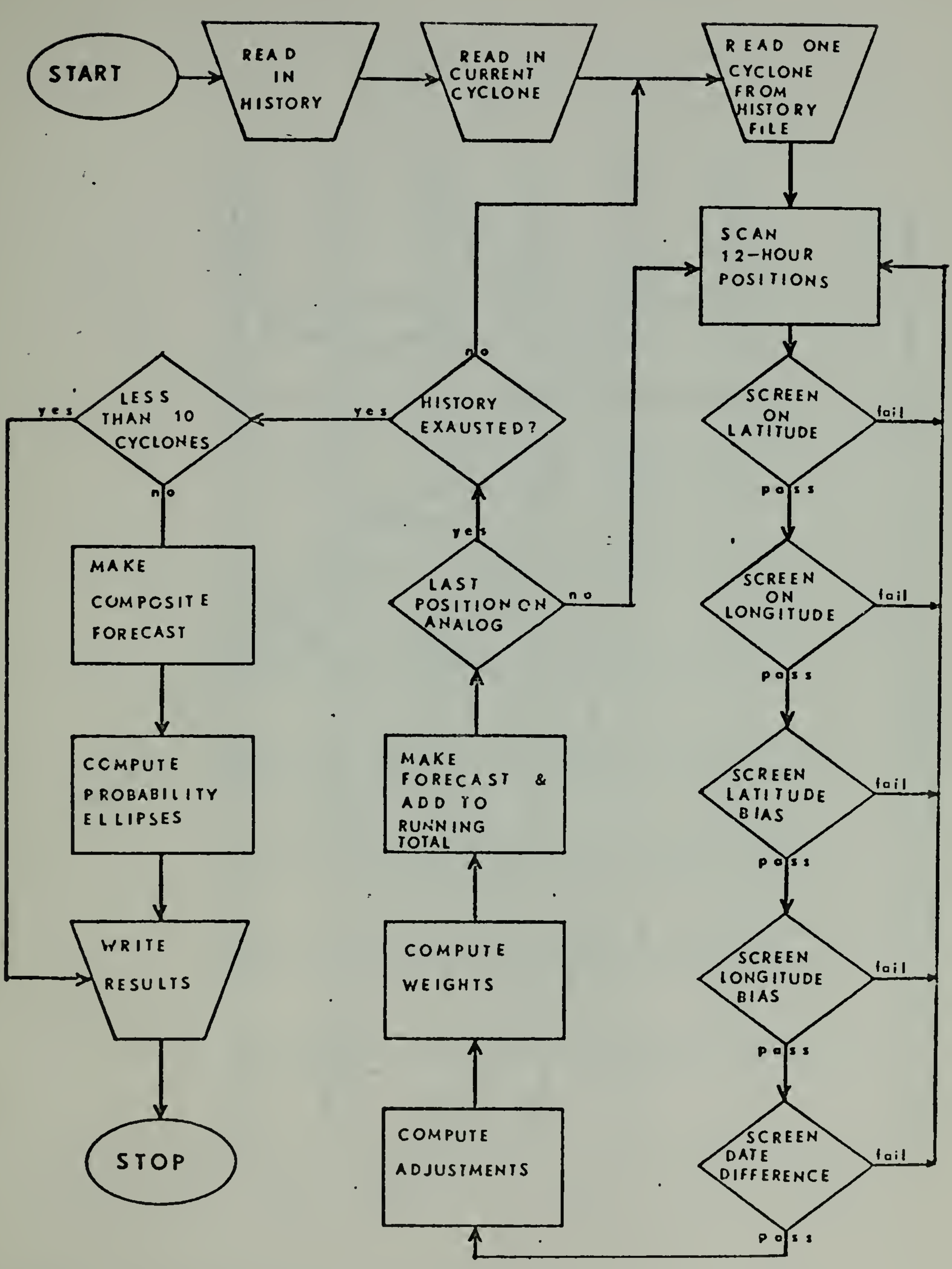

Figure 1. Flow diagram of eastern tropical North Pacific analog forecast technique.

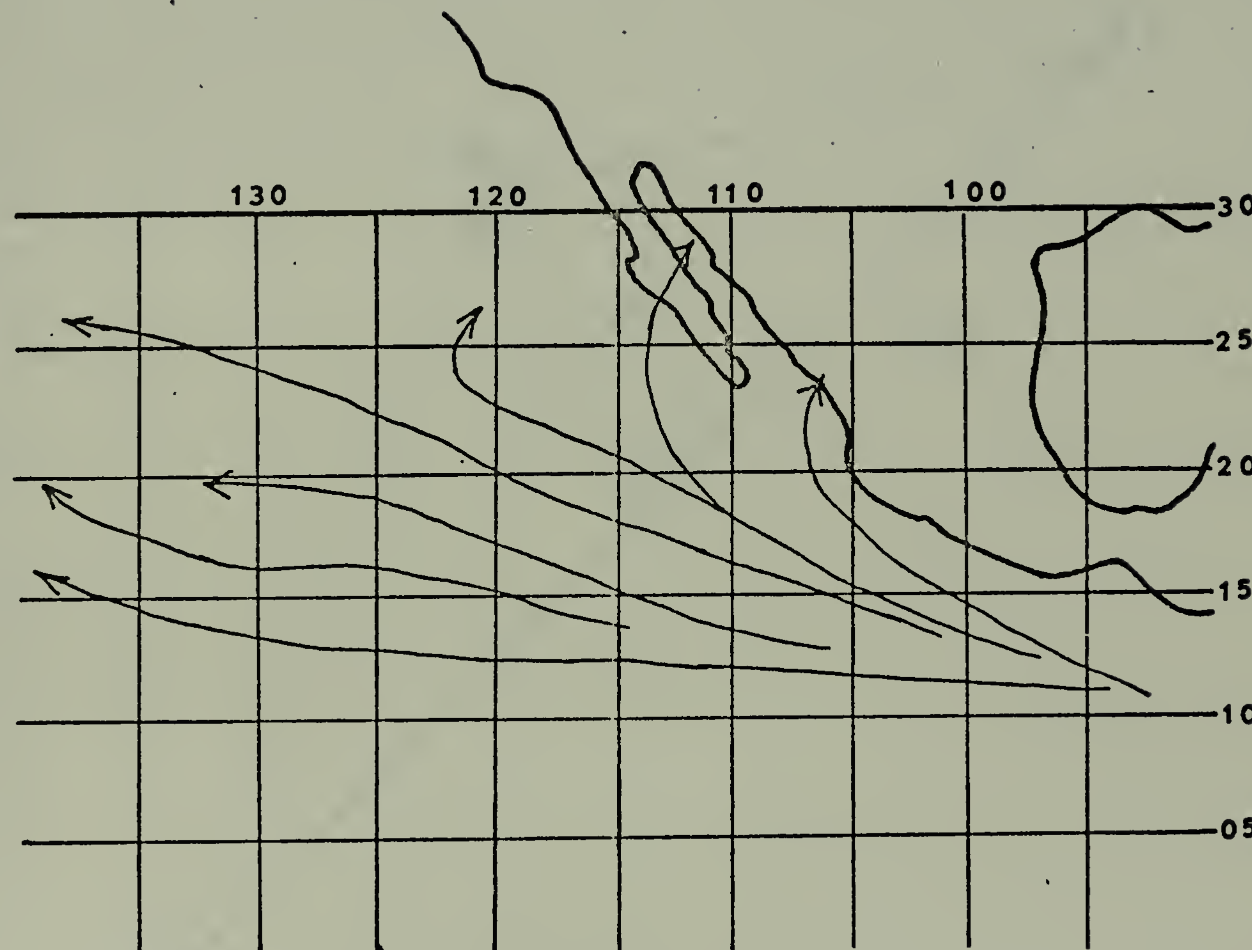

Figure 2. Mean eastern tropical North Pacific cyclone trajectories (based on five-degree squares). Hansen (1972).

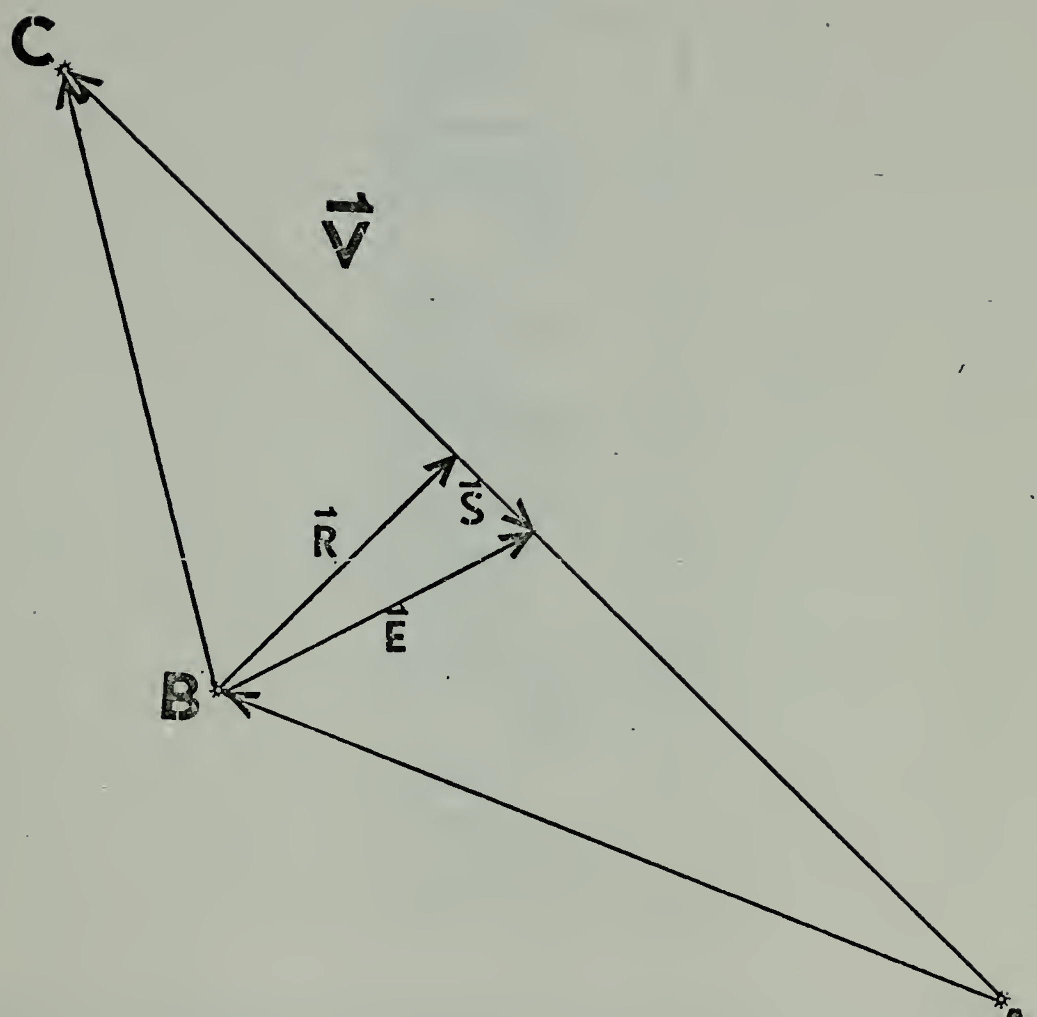

Figure 3. Diagram of vectors used in computing eccentricity of tracks. The 24-hour track is ABC. $\vec{R}$ represents across-track component; $\vec{S}$ represents along-track component and $\vec{E}$ is the total eccentricity (deviation from linear) of the track.

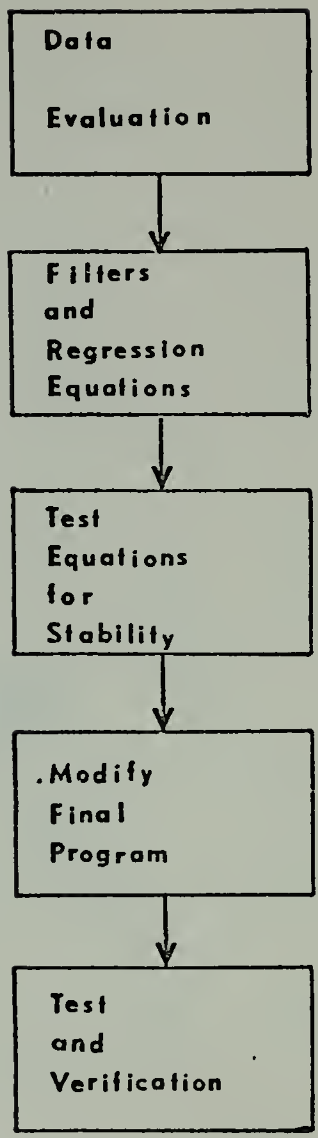

Figure 4. Flow diagram of eastern tropical North Pacific cyclone analog forecast program development.

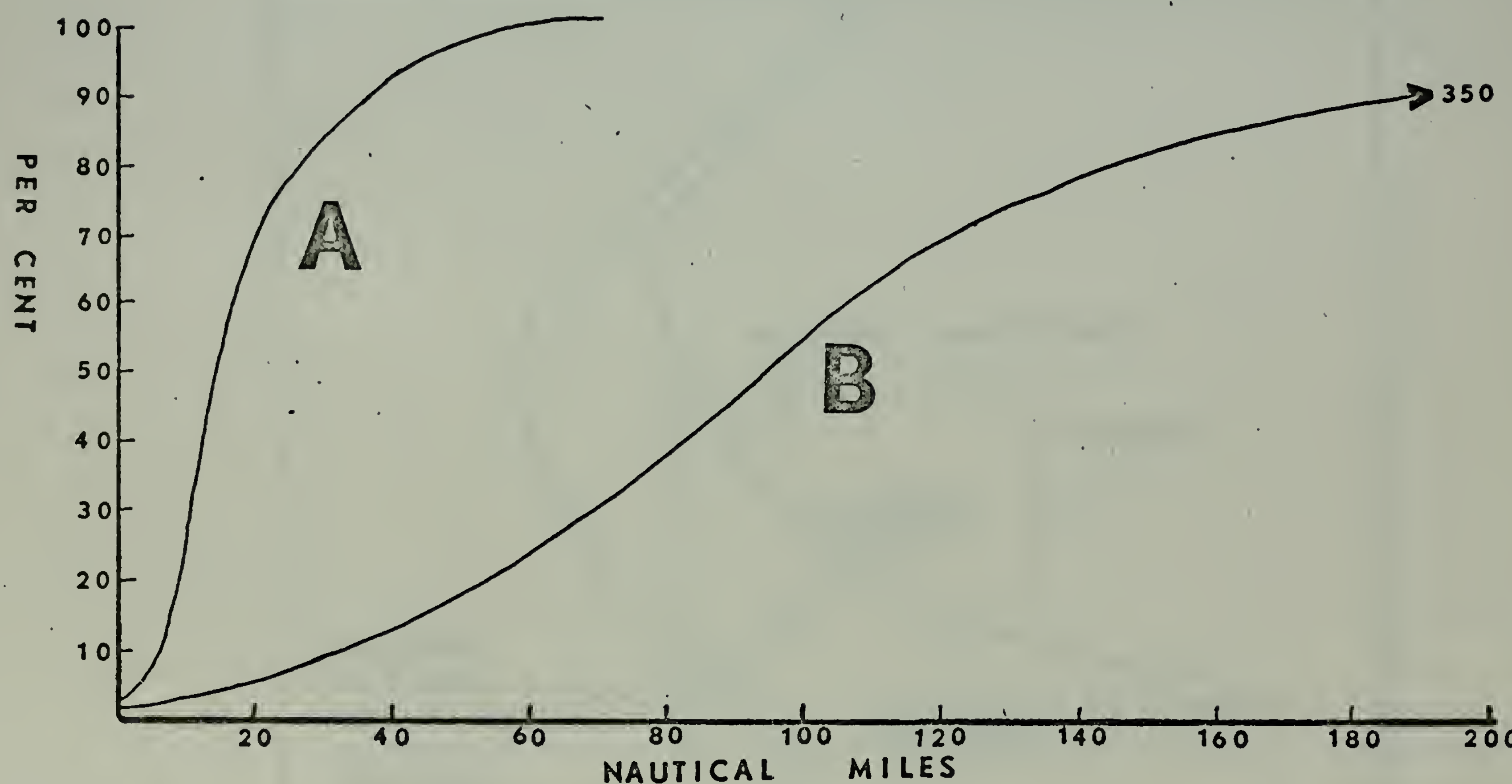

Figure 5. A. Cumulative frequency distribution of warning position errors, in nautical miles, in the western North Pacific Ocean area (WESTPAC).
B. Cumulative frequency distribution of the 24-hour forecast position errors (nautical miles) in WESTPAC).

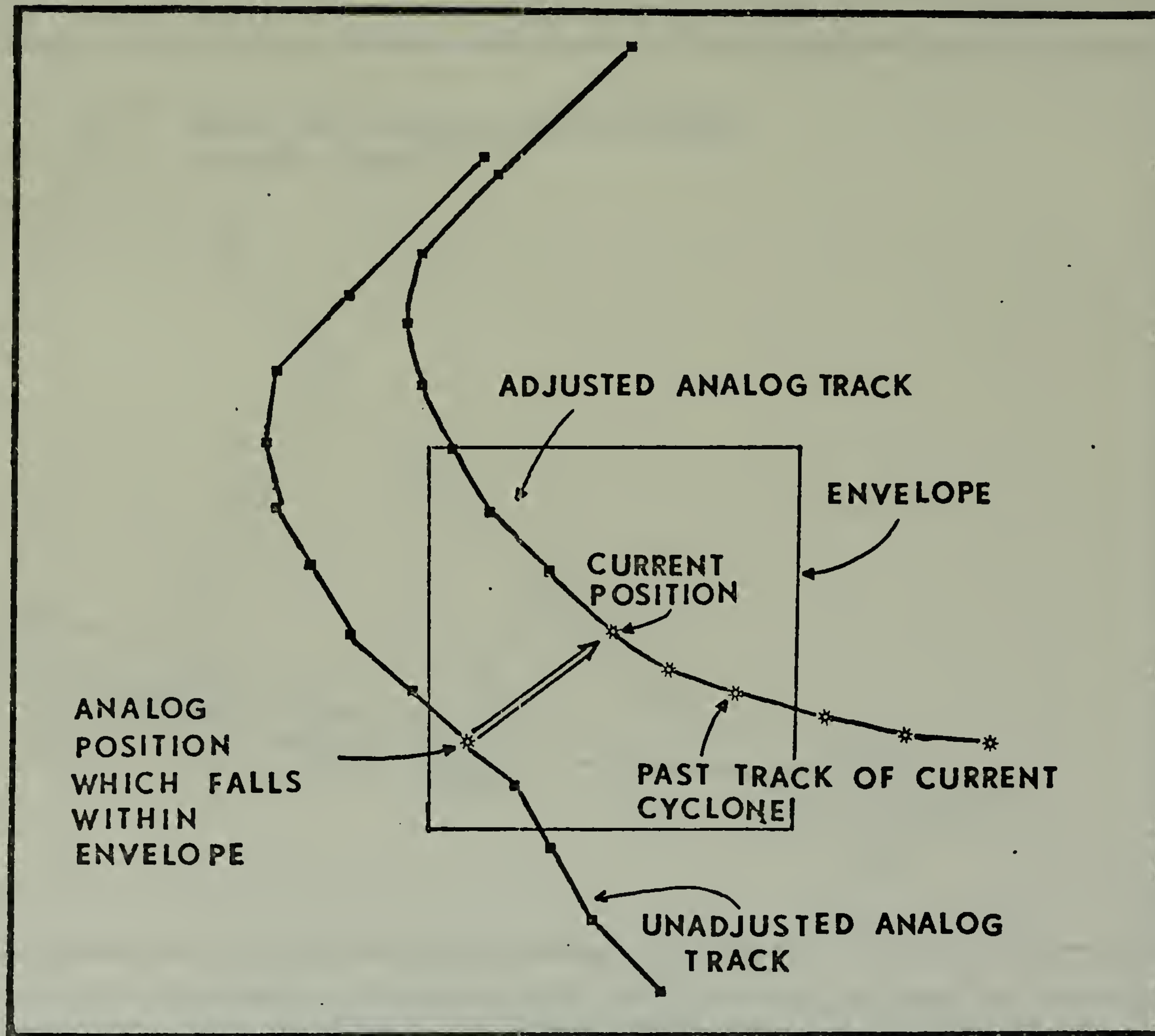

Figure 6. Example of translation adjustment to the analog track. The translation vector is from the analog position to the current position. This adjustment is applied to all future positions plus 12- and 24-hour history positions.

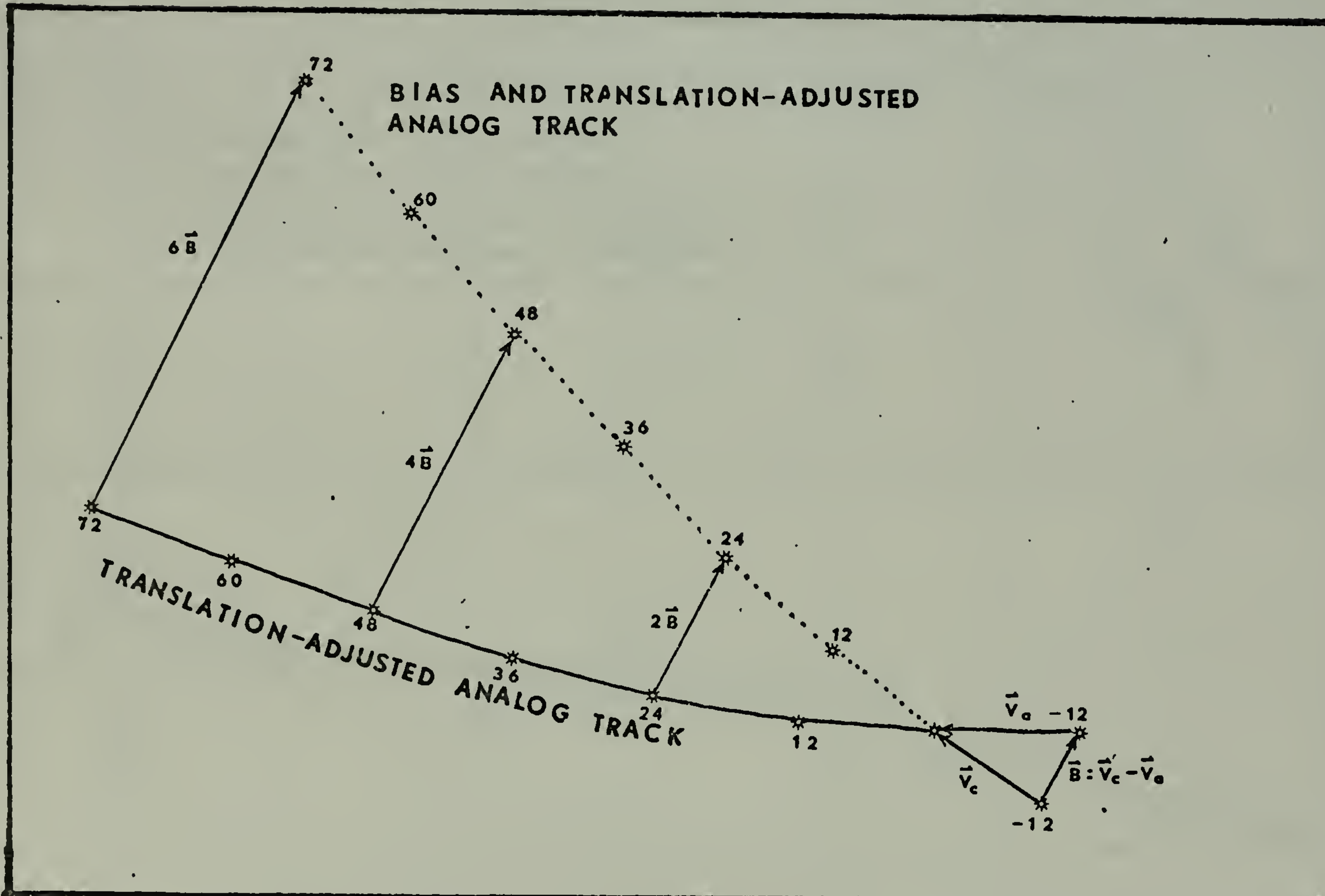

Figure 7. The bias adjustment to the analog track which has been adjusted for translation. $\vec{V}_c$ is the previous 12-hour movement of the current cyclone and $\vec{V}_a$ is the previous 12-hour movement of the analog cyclone after the translation adjustment has been made.

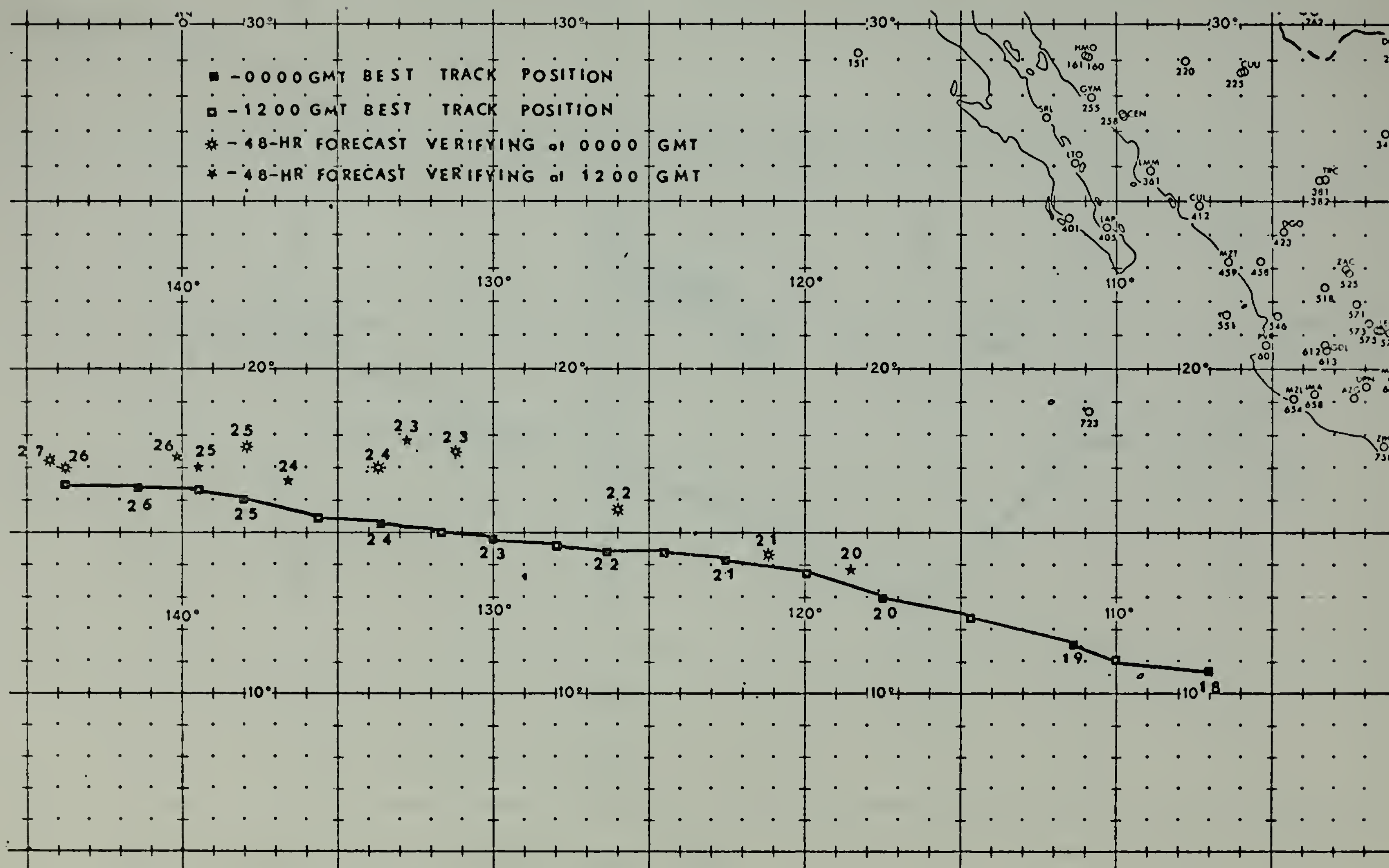

Figure 8a. Best track and selected 48-hour forecasts (from 0000 and 1200 GMT) for 1973 Hurricane Doreen in the eastern tropical North Pacific Ocean.

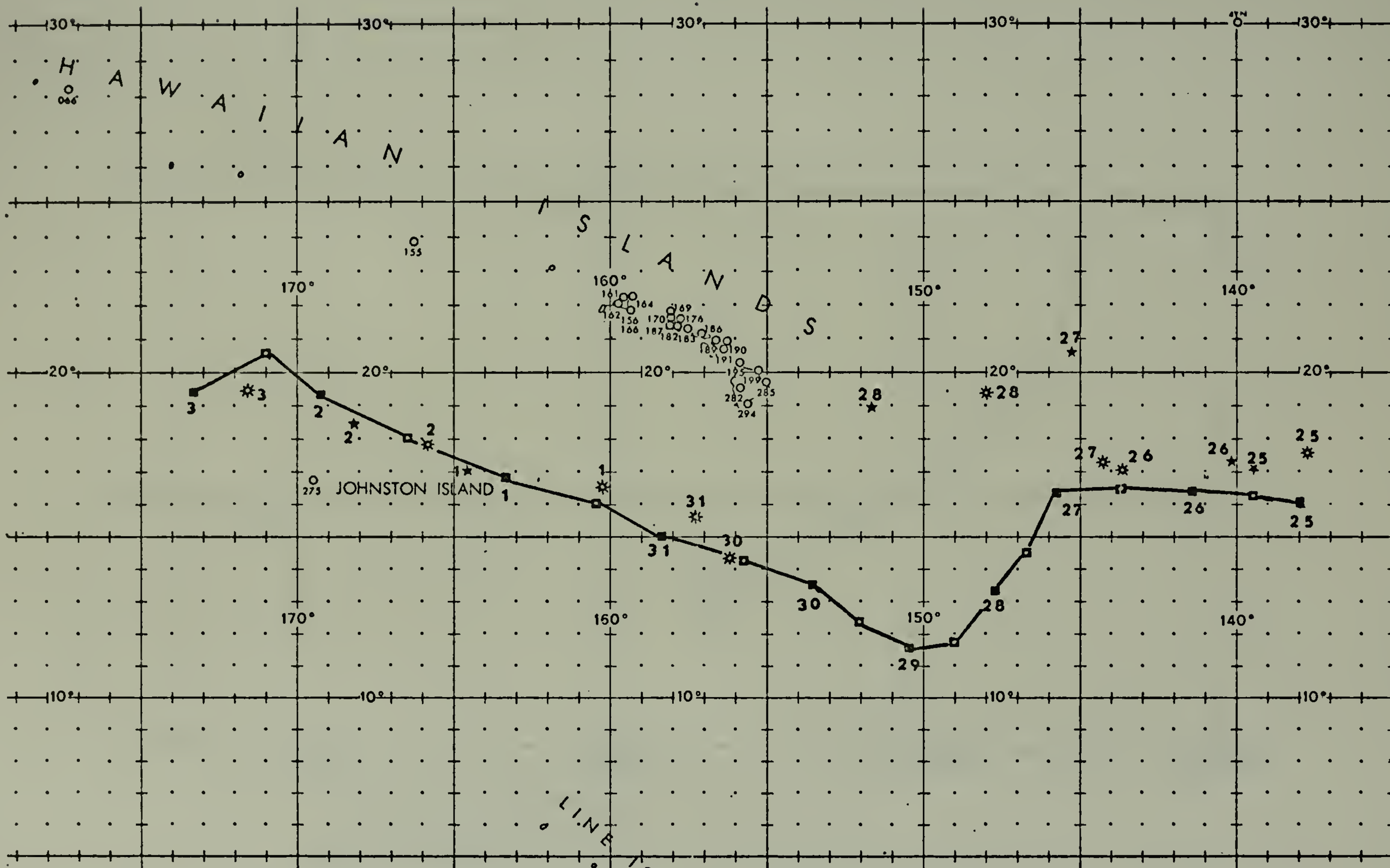

Figure 8b. Continuation of Hurricane Doreen track.

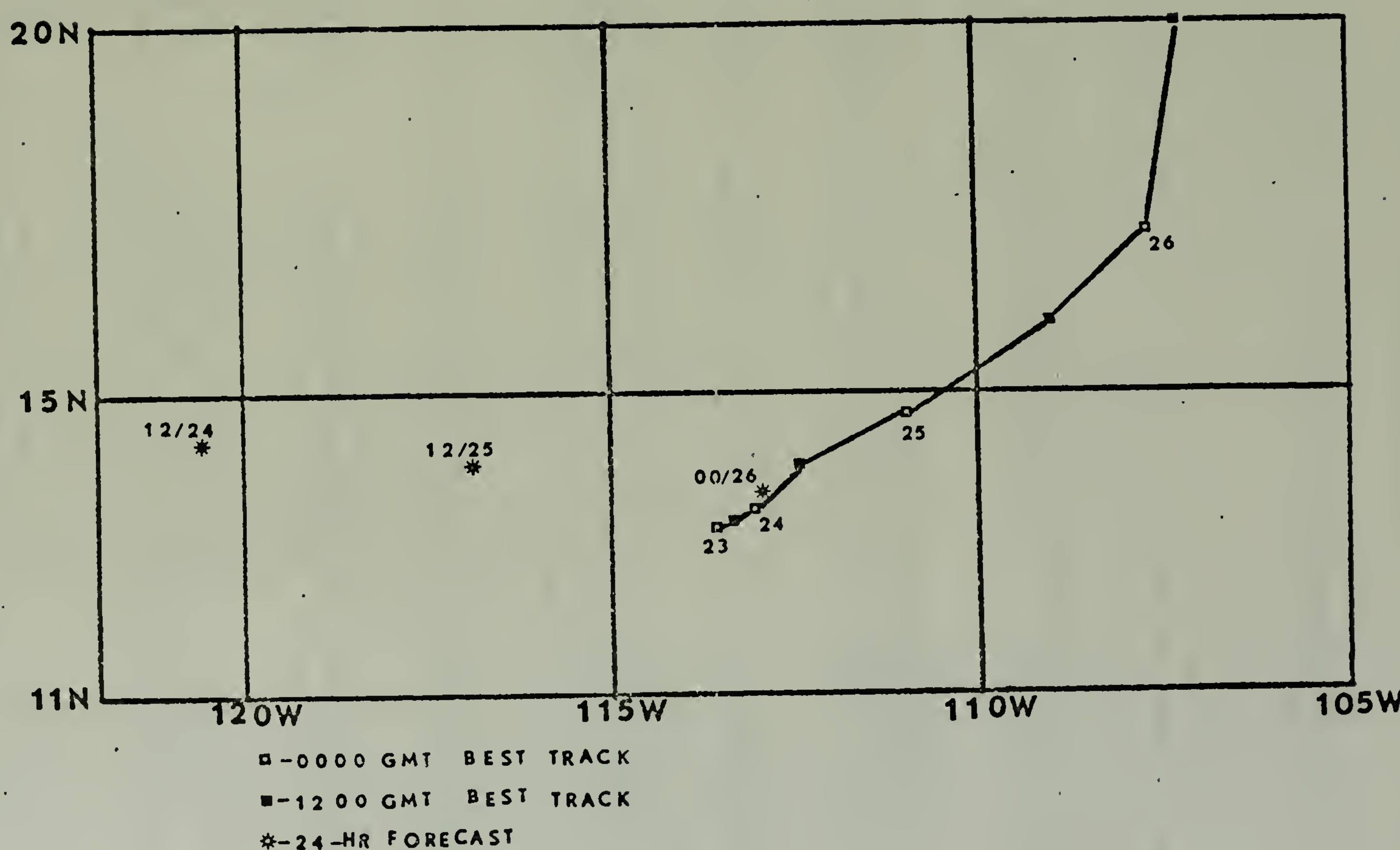

Figure 9. Best track and selected 24-hour forecasts (from 0000 and 1200 GMT) for Tropical Storm Jennifer in the eastern North Pacific Ocean.

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